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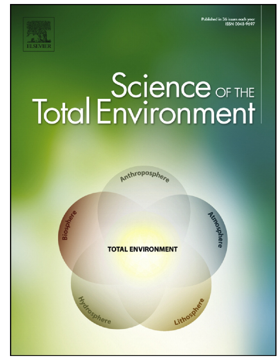

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Can forests buffer negative impacts of land-use and climate changes on water ecosystem services? The case of a Brazilian megalopolis

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Abstract

While the role of land-use conversion on water quality is reasonably understood, its role on water quantity is controversial. Climate change is also expected to impact water availability. Here we explore the interplay of hydrology, land-use change and climate change in one of the most populous urban areas in the world. We examined the potential of forests to buffer the negative impacts of land-use and climate changes on water-related ecosystem services in Tietê Basin, Brazil, which supplies water to the São Paulo megalopolis. We modelled six hydrological parameters using the WaterWorld Policy Support System, simulating the current baseline and six future scenarios (with different land-use and climate changes). Our results corroborate the general trend that increased forest cover improves water quality. Our modelling also predicts that increased forest cover increases water quantity in the southern part of the basin. The effects of climate change are observed mainly in urban areas, with a reduction in water quality. Because urban areas are not eligible for reforestation, they cannot benefit from its buffering effect on climate change. The increase in water availability is the greatest benefit of reforestation as a strategy to improve water-related ecosystem services in the region. Reforestation, however, will not suffice to restore all hydrological parameters in the basin, and additional sustainable agricultural practices are needed to mitigate impacts on water quality.

Keywords: forest cover, scenario modelling, water quantity, water quality, land cover, São Paulo.

Declarations of interest: none.

1. Introduction

The services provided by ecological systems are critical to the functioning of the Earth's life-support system (Constanza et al., 1997). Water security is an important ecosystem service and it is a pre-condition to accomplish social and economic development (ANA, 2010). Nevertheless, since mid-20th century, human activities have modified ecosystems in an unprecedented way (MEA, 2005), and water demand tends to increase mainly due to water pollution, contamination (Uriarte et al., 2011; Bakker, 2012) and withdrawal (Haddeland et al., 2014). Furthermore, a large portion of Earth's renewable fresh water is not accessible, because many rivers with very large runoff are located in remote areas, away from most human consumers, e.g. in the Amazon, Congo, and northern North America and Eurasia (Postel et al., 1996). Given this spatial mismatch between where the water is and where human consumers are, it is not surprising that water scarcity is a reality in many parts of the world (Veldkamp et al., 2017), representing one of the main environmental concerns in the 21st century (Srinivasan et al., 2012).

Forest cover is strongly associated with water quality (MEA, 2005) in two main ways: i) reducing soil erosion and sediment load, and ii) reducing pollutant input, because a forest cover is incompatible with intense land uses such as urbanization and agriculture (Stolton and Dudley, 2007). Therefore, one can expect forest restoration to improve water quality (Filoso et al., 2017). Additionally, the role of riparian vegetation in filtering contaminants and avoiding soil erosion and siltation is well known (Coelho-Netto, 1994).

While the positive relationship between forest cover and water quality is straightforward and well-established, the effect of forest cover on water quantity is scale dependent.

At the local scale, several studies show a negative relationship between forest cover and water quantity (e.g. Bosch and Hewlett, 1982; Bruijnzeel, 1990; Filoso et al., 2017). At this scale, removal of water from the soil to the atmosphere through forest transpiration prevails (Bruijnzeel, 2004). At the regional to continental scale, on the other hand, studies point to a positive relationship between forest cover and water quantity (e.g. Ellison et al., 2012). At this scale, multiple-mechanism feedbacks through the atmosphere prevail, affecting atmospheric circulation and, thus, precipitation patterns (Costa, 2005; Ellison et al., 2012). A major example is the Amazon forest, which acts as a biotic pump of moisture-laden air from the Atlantic Ocean into the South American continent (Makarieva and Gorshkov, 2007). This pump creates a massive "aerial river" that "drains" as precipitation in central and southeastern South America (Marengo et al., 2004; Nobre, 2014).

Rainforests and the climate establish a two-way interaction at large scale: climate drives the existence of rainforests, whilst rainforests are a component of the climate system (Costa, 2005; Nobre, 2014). In Brazil, water resources infrastructure has been planned through the projection of stationary time series. Climate variability (natural) and change (anthropogenic), however, increase not only the uncertainty of the projections, but also the likelihood of their negative impacts on water resources (Tucci, 2007).

The state of São Paulo (Southeastern Region of Brazil) has lost 86% of its original forest cover (SOSMA/INPE, 2018) and São Paulo city is one of the most populous cities in the World (UN, 2016). High demand for water, excessive effluent discharge (predominantly untreated domestic sewage) and extreme drought events have imperilled water supply in the last decades (ANA, 2015b). In the Metropolitan Region

of São Paulo city (MRSP), total rainfall has been increasing since 1961, but precipitation patterns are getting more irregular, so that very intense rainfall events are concentrated in short periods of time (i.e. a few days) that are separated by long periods of very hot and dry climate (Nobre and Marengo, 2017). In October 2013, rainfall went well below historical average levels in the region (monitoring data collected since 1930; ANA, 2015b). In the following year, the worst drought event since 1930 (ANA, 2015c) took place in the Southeast Region of Brazil. During the 2014/2015 event, resorting to water reserves (i.e. below operational levels) was necessary for the first time in the Paraíba do Sul River and Cantareira systems, the two major urban supply reservoirs in the region. Activities that depended on water storage, such as irrigation and hydropower generation (Brazil's main energy source) were also affected by the so-called "water crisis".

Considering the high levels of historical deforestation, as well as current restoration initiatives in the region (e.g. Pacto Mata Atlântica, 2009; Brasil, 2017), our aim is to investigate the ability of forest to buffer negative impacts of land-use change and climate change on water quantity and quality in the watersheds that supply São Paulo city. In this study we evaluate, for the first time, the potential of reforestation as a management strategy to improve water quality and quantity in the MRSP in a spatially explicit way. The specific objectives were to measure water quality and water quantity parameters today and in 2070 under three land use scenarios, varying from business-as-usual deforestation to 100% reforestation, with and without climate change.

2. Materials and Methods

2.1. Study Area

The study area is the Tietê water basin, located in São Paulo State, South-eastern Brazil. São Paulo is the most economically developed state in Brazil, holding 60% of Brazil's gross domestic product (R$ 1,985,359; SEADE, 2018) and 22% of its human population (ca. 45 million; IBGE, 2018) in only ca. 3% of the Brazilian territory. The MRSP is within the Tietê basin, the largest urban agglomeration in the Southern Hemisphere, and among the largest in the world, with 21.6 million people (IBGE, 2018). The basin is inside the Paraná hydrographic region (ANA, 2015a), the total area is ca. 21,000 Km^2, the total population is >30 million people and it comprises four sub-basins: Piracicaba (ca. 12,600 Km^2), Capivari (ca. 1,600 Km^2), Jundiaí (ca. 1,100 Km^2; hereafter, PCJ) and Alto Tietê (ca. 5,700 Km^2; Figure 1). Part of PCJ's water is diverted to Alto Tietê through the Cantareira System to supply water for more than 9 million people in the MRSP (TNC, 2013). Urban areas cover ca. 2,850 Km^2 (or 13% of the area) and protected areas cover 10,900 Km^2 (only ca. 2% in the "Full Protection" category).

Originally, the region was mostly covered by the Brazilian Atlantic rainforest, but due to intense human activities it is currently extremely impacted (there is only 28% of the original rainforest cover left; Rezende et al., 2018). Alto Tietê has an urbanization index (i.e., the percentage of the total population that lives in urban areas) of 99% (Braga, 2017), and several stretches of rivers within the Tietê water basin are considered to be in critically poor conditions due to high demand and high domestic sewage load (ANA, 2015b).

The main beneficiaries of water-related services in the Tietê basin are the > 21 million people that inhabit the MRSP. The projected population growth by the mid-21st century

for the region raises concerns about the lack of access to drinking water and vector proliferation, leading to increased incidence of infectious diseases and public health issues (Nobre et al., 2010).

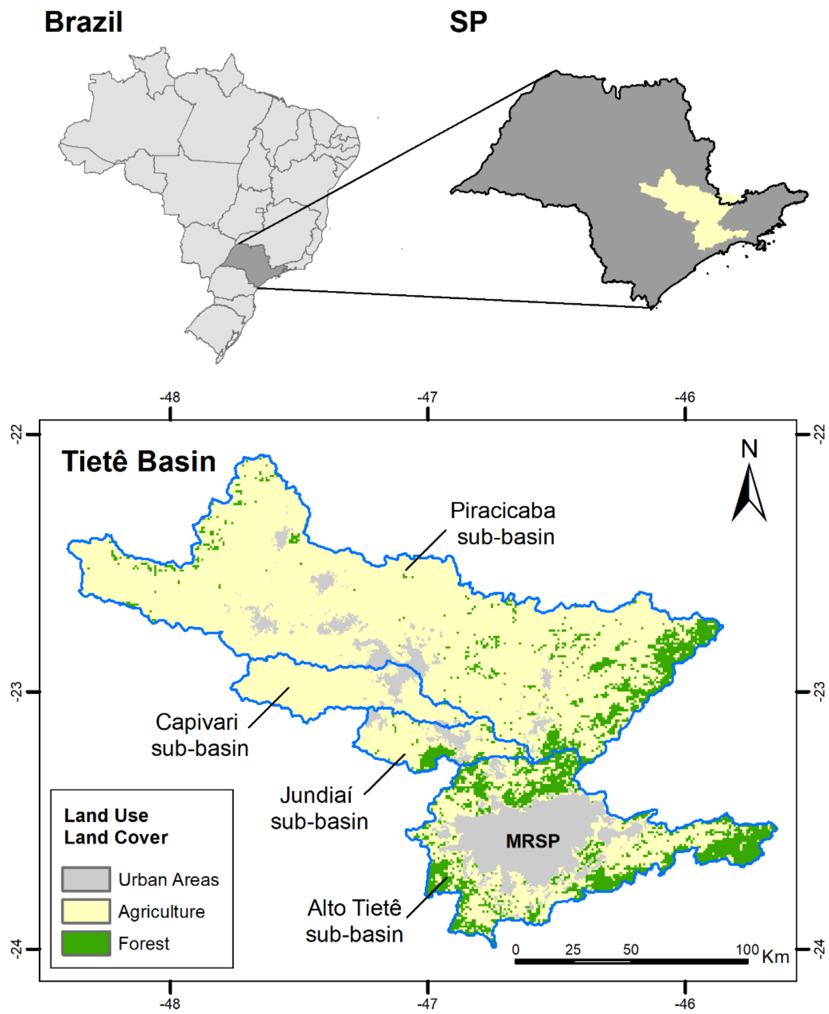

Figure 1 - Study Area. The Tietê water basin is located in São Paulo State (SP) in Southeastern Brazil. It is composed of four sub-basins (blue lines) that supply water to the Metropolitan Region of São Paulo (MRSP). Data source: map created with data from IBGE (2014, 2016) and Lehner and Grill (2013).

[Use colour for Figure 1 if printed.]

2.2. Scenario Building

Scenarios were developed using the built-in scenario generator of the WaterWorld Policy Support System v2.92 (WaterWorld), a spatially explicit, physically based globally applicable hydrological model. The model is 'self-parameterising', in that it includes global datasets built-in for all the required variables including land-use/land-

cover and climate (Mulligan, 2013). The WaterWorld model has been specifically designed for scenario analyses, including the estimation of the maximum potential of forest recovery (e.g. van Soesbergen and Mulligan, 2018; Mulligan, 2013). Furthermore, the built-in land use scenario tools allow for quick, yet robust modelling (using a process-based model) of changes in water quantity and quality as a result of land use changes. We simulated one baseline (representing climate and land use in 2010) and three “alternative” scenarios (representing deforestation as expected under a business as usual scenario, 50% reforestation and 100% reforestation respectively) for the year 2070 (climatological average for 2061-2080; Hijmans et al., 2005). Deforestation and reforestation differ in one key aspect: the time they take to occur. While deforestation can virtually take place in the timescale of hours or of a few days, reforestation is a much more complex and time-consuming process. Additionally, there are historical deforestation databases available (e.g. SOSMA/INPE, 2018) to back up more realistic annual rates, as opposed to reforestation rates, for which efforts so far are much smaller than the scenarios proposed in this study. Therefore, deforestation and reforestation scenarios also differed in the way land conversion rules were applied. We set an annual deforestation rate, so that the total deforested area in the basin in the year 2070 was not pre-established in the model settings. On the other hand, the total amount of reforested areas by 2070 was pre-defined in the settings (to 50% and 100%).

We developed one additional version of each land use scenario incorporating the influence of climate (deforestation with climate change, 50% reforestation with climate change, and 100% reforestation with climate change). Therefore, we had seven different scenarios: one baseline plus the two versions of each of the three alternative land use scenarios. Scenarios were developed in order to evaluate the potential of

increased forest cover to improve water-related ecosystem services and buffer the effects of climate change that are projected for the region. The climate change scenarios in WaterWorld are based on IPCC CMIP5 scenarios, downscaled using WorldClim data (Hijmans et al., 2005). Scenarios without climate change are not realistic, since climate change is already under way (IPCC, 2013), but they were modelled to assess whether forests could buffer the effects of climate change on water ecosystem services. In a similar way, a 100% reforestation scenario is not realistic in a basin with >21 million inhabitants in the MRSP only, but it was created to evaluate the maximum potential of forests to buffer the negative impacts of climate change on water ecosystem services. Essentially, if in the 100% reforestation scenario there is no improvement in a hydrological parameter of interest, reforestation can be discarded as a specific management strategy for that particular parameter.

In WaterWorld, each pixel (1 km^2) has a combination of three land-cover types: bare ground, herbaceous cover and tree cover (Townshend, 2011). These cover types determine the structural properties of vegetation that control evapotranspiration and fog inputs (impacting water quantity). WaterWorld also defines a series of land uses (urban, cropland, pasture, mining, oil and gas, roads and protected areas) that impact upon contaminant inputs and thus water quality (see Mulligan, 2013). The baseline scenario represents the current amount of forest cover, using 2010 as the reference year. For the deforestation scenario, we used the QUICKLUC (v2.1) land-use change model, WaterWorld's built-in land use modelling tool, which projects the magnitude and spatial pattern of deforestation into the future based on recent (2000-2012) annual deforestation rates according to the Global Forest Change dataset (GFC; Hansen et al., 2013) and a spatial model for continued deforestation (Mulligan, 2015). These rates were assessed for regional administrative areas (as defined by FAO, 2014).

QUICKLUC defined the spatial distribution of the pixels that were subject to deforestation according to distance-based rules (Mulligan, 2015) that generate new deforestation from existing deforestation frontiers. Because roads are an important deforestation trigger (Ibisch et al., 2016), we also chose the QUICKLUC option to increase deforestation probability with proximity to roads, using both current (FAO, 2014) and planned (Mulligan, 2012) roads. Recent annual deforestation rates were kept constant, i.e. they were multiplied by one, simulating a “business-as-usual” scenario. Eligible pixels were subjected to clear-cut deforestation (100% conversion), following the historical pattern and trend of land-use change in the Atlantic Forest (Ribeiro et al., 2009). We assumed that all deforested pixels would be replaced by agriculture, setting the rule to “the most common agriculture locally” (either cropland or pasture), also in accordance with the historical pattern of deforestation in the biome.

For the reforestation scenarios, we analysed the remaining (baseline) forest cover within the Tietê basin, excluding from the reforestation rules the areas that are unsuitable for reforestation: already forested areas, strictly protected areas, and urban areas. We considered as forested areas the ones that currently have ≥75% tree cover per pixel, and as strictly protected areas the “integral protection areas” in the Brazilian System of Protected Areas (Brasil, 2000). These protected areas preserve the highest percentage of forest cover and, consequently, coincide with “forested areas”. The remaining areas were subjected to the two reforestation scenarios. We considered 50% reforestation an already bold target, and used the 100% reforestation to estimate the maximum potential of forest cover to improve water related ecosystem services and buffer the effects of climate change.

In order to consider the impacts of global climate change in land-use/land-cover change, climate change was “stacked” in each of the alternative scenarios so that the hydrological outputs incorporate the effects of both climate (i.e. rainfall and air temperature) and land-use (i.e. deforestation and reforestation) change in water-related ecosystem services. We used the climatic data available in WaterWorld, which provides the mean of 17 downscaled General Circulation Models (Hijmans et al., 2005) from the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2009) for each RCP. We used the “business as usual” climate change scenario (RCP 8.5; Riahi et al., 2011), as it estimates future trends of global CO_2 emissions as close to the currently observed patterns (Peters et al., 2012).

Currently, the population is still growing in São Paulo State. However, the growth rate is decreasing and by mid-21st century it is projected to become negative (i.e. the population will begin to decrease; IBGE, 2019). Therefore, we kept population growth constant in our scenarios for the study area, making our results conservative in that regard.

2.3. Hydrological Modelling

Analyses were run annually at 1-km^2 spatial resolution for the entire basin using the WaterWorld (v2.92) model. For water-related ecosystem services we analysed six annual hydrological outputs produced by the model — human footprint on water quality – HFWQ (hereafter, pollution footprint), human footprint on water quality [diarrheal disease] – HFWQ[DD] (hereafter, sewage footprint), water stress, erosion, water balance and runoff (Table 1).

In order to statistically test the difference between the resulting maps we used 500 points randomly distributed in the study area (0.02 points/km^2), excluding urban areas and strictly protected areas where deforestation and reforestation are unlikely to happen. We then compared results using a Kruskal-Wallis test and the post-hoc Dunn test. We considered the level of significance of 5%. All statistical and GIS analyses were run in the software R (R Core Team, 2017) and ArcGIS 10.5.

3. Results and Discussion

3.1. Water Quality

WaterWorld projected changes in water quality in the Tietê Basin by 2070, with greater intensity for sewage and pollution footprints, and low intensity for soil erosion (Figure 2, Table 2, Appendix). As expected, the deforestation scenario worsened water quality for all parameters, while the reforestation scenarios improved it (Figure 2). For sewage and pollution footprints the results were statistically significant for all scenarios except for the water pollution with 50% reforestation (Figure 2).

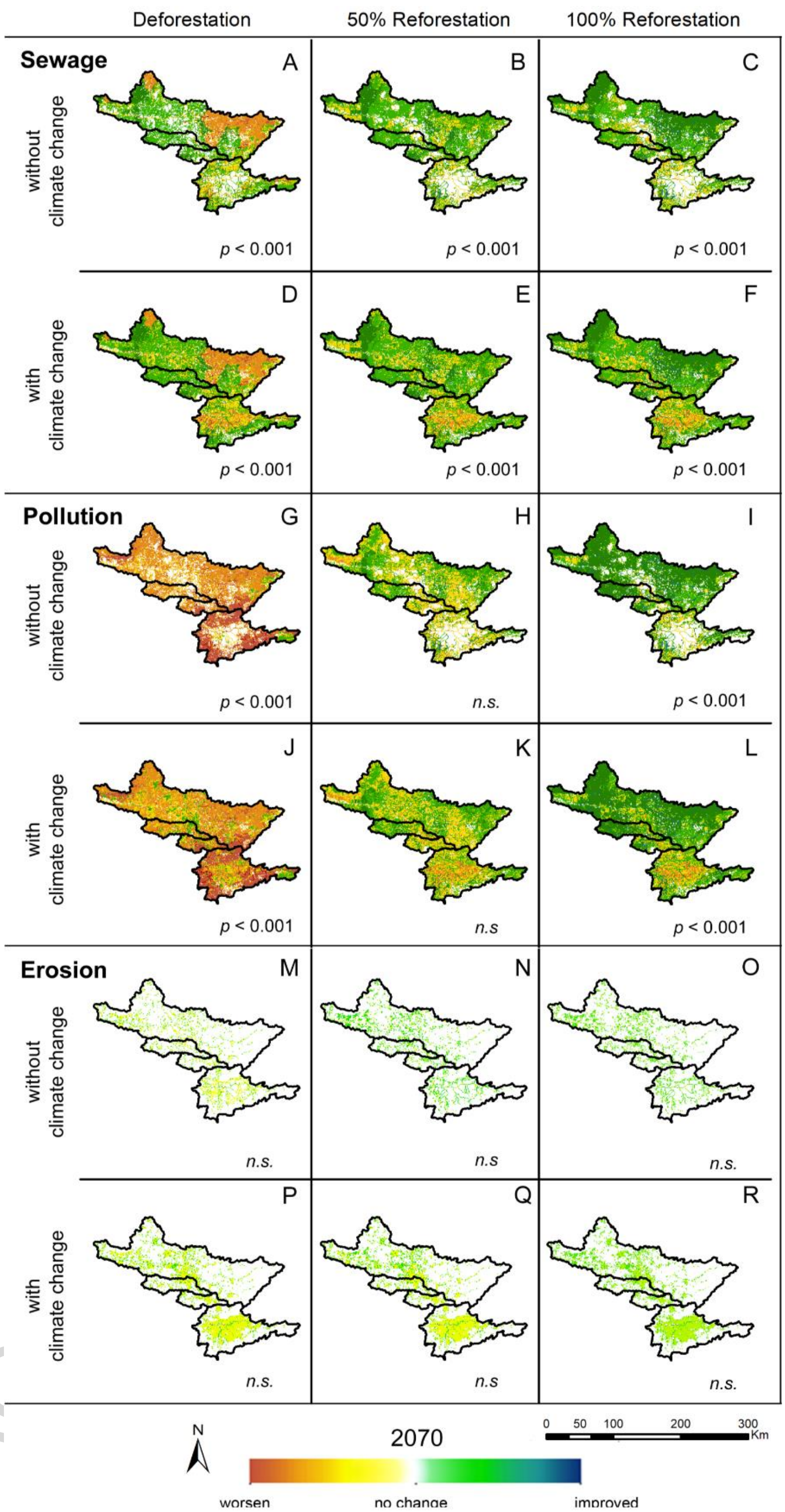

Figure 2 - Projected change in water quality parameters by 2070 in Tietê basin under different forest cover and climate change scenarios. Parameters: pollution footprint (% contamination) (A – F); sewage footprint (% contamination) (G – L); Erosion – annual net soil erosion (mm/yr) (M – R). Forest cover scenarios: deforestation, 50% reforestation, and 100% reforestation. Climate change scenarios: with climate change and without climate change. Post-hoc Dunn

test results (p-values) for the comparison between the 2010 baseline and the 2070 projection under the different scenarios.

[Use colour for Figure 2 if printed.]

Sewage footprint, a key parameter of water quality, is a measure of diarrheal disease vectors (from people and livestock), which have potential implications for childhood diarrheal disease in developing countries (Herrera et al., 2017). Because of the current predominance of croplands over pasturelands in non-forested areas in Tietê basin, deforestation scenarios project forest conversion into croplands only. We also held human population constant. As a result, deforestation scenarios do not project an increase in contamination by people and livestock in most catchment areas in the Tietê basin (Figure 2). A notable exception is the eastern portion of Piracicaba sub-basin (orange area in Figure 2A). This broad area corresponds majorly to protected areas (west: Piracicaba Juqueri Mirim – Area I; east: Campinas, Fernão Dias and Piracicaba Juqueri Mirim – Area II). In spite of being protected (Law nº 9.985; Brasil, 2000), this area is currently a mosaic of forest cover and pasturelands. Therefore, in scenarios of deforestation, according to the modelling we performed, these areas would be converted to pasturelands, which account for the observed increase in sewage footprint. Legislation alone does not ensure forest cover integrity even in protected areas and, if this scenario materializes in 2070, forests' associated hydrological benefits of water purification can be impaired.

Pollution footprint, on the other hand, considers plantation inputs (e.g. pesticides, herbicides, fertilizers) (Mulligan, 2009) and, therefore, under the deforestation scenario there is a generalized increase in pollution footprint over the basin (Figure 2). Indeed, in Brazil agricultural lands represent one of the major sources of non-point pollution

(ANA, 2015b) often resulting in the quality of the water falling below the standards for human consumption (Honda and Durigan, 2017).

The main impact of climate change was observed in urban areas, which are not eligible for reforestation. In rural areas, water quality consistently improved with reforestation, independently of climate change (Figure 2). In urban areas, on the other hand, climate change led to a decline in water quality (Figure 2, see Figure 1 for MRSP). Apparently, therefore, reforestation can buffer the negative effects of climate change on water quality, but because urban areas are not eligible for reforestation, they cannot benefit from a reforestation strategy.

The decline in water quality due to land conversion from forests to agriculture can also be caused by increased erosion and soil loss (Novotny, 1999). Among different land cover types, agricultural lands tend to yield the highest erosion rates, and forests are among the lowest ones (García-Ruiz et al., 2015). Therefore, this process could compromise the role of important rivers in the basin (such as Tietê, Pinheiros and Tamanduateí) in supplying water to the most populous region in Brazil. In this study, though the colors indicate the tendency of reforestation to reduce soil erosion and of deforestation to increase it, WaterWorld was not sensitive to the effects of land conversion on soil erosion for the scenarios we modelled, and changes in this parameter were not statistically significant (Figure 2). Considering that in Brazil the standard agricultural practices disregard soil conservation (Martinelli et al., 2010; Merten and Minella, 2013), sustainable agricultural practices are an alternative guideline to slow down erosion and siltation in the Tietê basin.

3.2. Water Quantity

The modelling also projected changes in water quantity by 2070 in the Tietê water basin, (Figure 3, Table 3, Appendix). In general, the deforestation scenarios tend to increase water quantity. Since the deforestation modelling converts forests into agriculture, the projected increase in water quantity could be explained by reduced evapotranspiration — both due to the removal of trees (Schlesinger and Jasechko, 2014) and the conversion to herbaceous cover with lower transpiration (van Soesbergen and Mulligan, 2014) — and thus increased effective rainfall. Although this is the general spatial trend, this result was not statistically significant in most cases (i.e. for most of the parameters and scenarios), except for water balance and water stress in the scenarios without climate change (Figure 3). As previously mentioned, scenarios without climate change are assumed here to be non-realistic, once climate change is under way, as pointed out previously (IPCC, 2013).

The reforestation scenarios, on the other hand, generally decreased water quantity throughout the whole basin, with statistically significant results in all cases (Figure 3). The improvement in water quantity in the southern portion, particularly in urban areas, was found only under the more realistic climate change scenario (Figure 3), and again, all results were statistically significant.

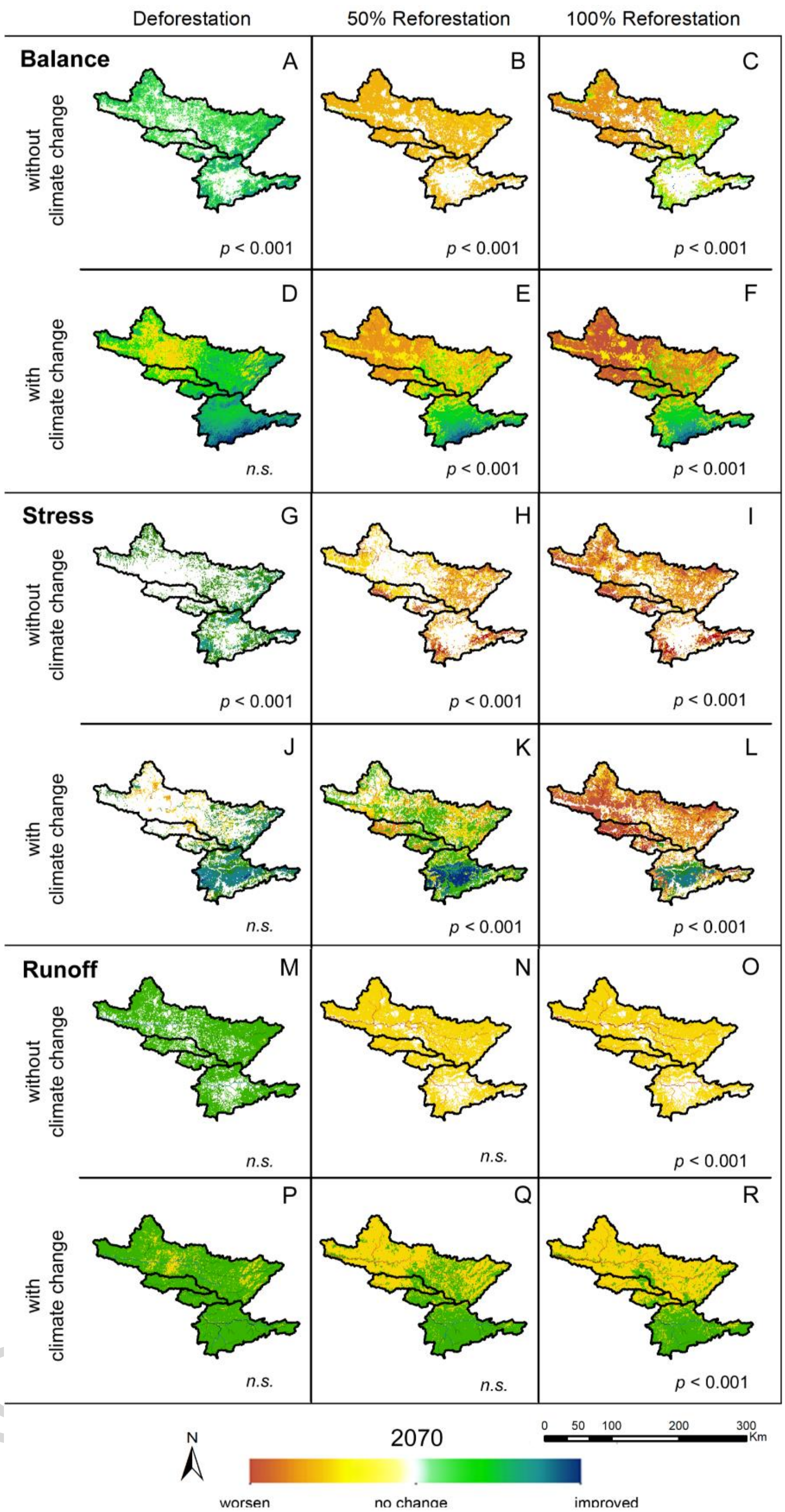

Figure 3 - Projected change in water quantity parameters by 2070 in Tietê basin under different forest cover and climate change scenarios. Parameters: water balance (mm/yr) (A – F); water stress (% unavailable) (G – L); runoff (Km^3) (M – R). Forest cover scenarios: deforestation, 50% reforestation, and 100% reforestation. Climate change scenarios: with climate change

and without climate change. Post-hoc Dunn test results (p-values) for the comparison between the 2010 baseline and the 2070 projection under the different scenarios.

[Use colour for Figure 3 if printed.]

Once again, the main projected impact of climate change was in urban areas, where there was essentially no projected change in water quantity in scenarios without climate change, but interestingly, water quantity improves, rather than worsens with climate change in the southern part of the basin (Figure 3; see Figure 1 for MRSP). The changes in the mean annual rainfall in the southern part of Tietê basin in 2070 compared to the baseline are expected to be higher than the changes in the northern part, based on the mean of the 17 downscaled General Circulation Models from CMIP5 used in WaterWorld (Hijmans et al., 2005). As a consequence, water stress in the region decreases as it is inversely related to water balance.

Outside the MRSP, we observed contrasting trends between the scenarios of reforestation with climate change for water stress: with an improvement (i.e. decrease in water stress) in the 50% reforestation (with climate change) and an increase in water stress in the 100% reforestation (with climate change) one. Climate change has potential to offset water quantity losses from land-use/cover change alone because it leads to increased precipitation in the basin, in general, compared to the baseline.

Runoff and water balance are projected to increase in the southern portion of the basin under reforestation scenarios with climate change (though not significant for 50% reforestation; Figure 2). This could provide more water available for reservoirs in the region, which is relevant given the concerns raised by the serious 2014/2015 water crisis in the MRSP (ANA, 2015c). It is important to note, however, that we have used

only the annual mean values whereas WaterWorld also provides monthly data. Seasonality in precipitation means that the increase in water quantity may not be even throughout the year, and this may be reinforced by climate change. Considering that precipitation patterns in the region have been getting more irregular, with very intense rainfall events concentrated in a few days that are separated by long hot dry periods (Nobre and Marengo, 2017), investments should be made towards improvement of water capture in reservoirs to maintain supply throughout the year. At the same time, the irregularity in rainfall also contributes to peak flows, increasing the likelihood of flood events (not modelled in this study). Indeed, the MRSP was the most affected by flood events between 1991 and 2012 (CEPED, 2013), and this is precisely the region where we project an increase in water quantity under reforestation scenarios with climate change. Reforestation, however, may buffer seasonal flows because it is expected to improve soil conditions and thus infiltration in the wet season. This, in turn, should improve the reliability of flows in the dry season and possibly other anomalous periods and thus relieve water stress. Therefore, the projected increase in water quantity in the southern portion of the basin under reforestation scenarios may benefit the population of the MRSP, as long as the forest can also buffer a possible increase in flood events, which is something that was not explicitly modelled in this study.

It is important to note that an increase in water quantity does not necessarily translate into an increase in water availability. Water with poor quality is actually less available for consumption, unless it is treated prior to consumption. The eight water supply systems of the MRSP, for example, currently cannot supply more than half of the demand, due to poor water quality (Prefeitura de Santo André, 2014). Thus, the increase in water availability is the greatest benefit of reforestation as a strategy to improve water-related ecosystem services in the region. Reforestation has the

potential of increasing water availability through an increase in water quality in the majority of the basin (Figure 2), buffering the effects of the generalized water quantity decrease, i.e. in areas where reforestation rules applied.

3.3. Model Uncertainties and Limitations

Any model has uncertainties and WaterWorld is not different. The built-in datasets are extremely useful in areas with shortage of data, as in the Tietê basin but, at the same time, global datasets may have lower accuracy at the local scale. Ideally, the model should be validated but Brazil does not systematically take (or distribute) data on erosion, water balance, water stress or runoff. Nevertheless, WaterWorld has been validated extensively in similar study regions with satisfactory results (e.g. van Soesbergen and Mulligan, 2016; van Soesbergen and Mulligan, 2018; Mulligan and Burke, 2005). In addition, focusing on the relative changes between baseline and scenario rather than the absolute magnitude of differences reduces some of the uncertainties around input data (e.g. rainfall) as relative changes are much more dependent on model logic and scenario characteristics and, thus, are less sensitive to differences between input data values (see Mulligan, 2013; van Soesbergen and Mulligan, 2018).

Another limitation is around the modelling of the relationship between forest cover and ecosystem services. We used a time span of 60 years (from 2010 to 2070), and a pre-defined percentage to meet our targets (i.e. 50% and 100% reforestation). Reforestation, however, is a complex and long process with a non-linear relation with ecosystem services provision (MEA, 2005), which is not taken into account by WaterWorld. Therefore, there is considerable uncertainty on whether water ecosystem services would be fully provided by 2070. The study is, in fact, more focused on the

potential of the different scenarios (i.e. 50% and 100% reforestation) in improving water-related ecosystem services than on the time it will take to reach it, but it was necessary to set a time in order to incorporate the climatic data.

The choice of climate change scenario may also be a source of uncertainty. RCP 8.5 projects CO_2 emissions which are similar to the patterns currently observed (Peters et al., 2012). If the Paris agreement succeeds in significantly reducing greenhouse gas emissions by 2030, however, the increase in mean global temperature by 2100 (2.6-3.1 ^{o}C; Rogelj et al., 2016) could be within the range of RCP 6.0 (Knutti and Sedláček, 2013) and, therefore, the estimate in this study would be “pessimistic” instead of “business as usual”. In that case, the negative impacts of climate change on urban areas in the Tietê basin would be slightly reduced. For the reasons listed above, our results must be carefully interpreted. Our objective was to assess the interplay between two stressors – climate and land-use change – on the contribution of forests to water availability (i.e. quality and quantity) in broad terms. We conclude that reforestation has great potential as a management strategy for water-related ecosystem services in the study area.

3.4. Policy Remarks

Reforesting the Tietê basin is possible and Brazil has already made a number of international commitments in that regard. The country has bold targets under the Paris agreement of the United Nation’s Climate Change Convention (UN, 2015), including restoring and reforesting 12 million hectares of forests by 2030. This target is reinforced under the Bonn Challenge, a global restoration effort. Brazil is also signatory of the United Nations Strategic Plan for Forests, which aims at increasing forested areas by

3% worldwide by 2030 (UN, 2017), and the Aichi Targets, which claims that the rate of loss of natural habitats, including forests, must halve by 2020 (CDB, 2016).

These international commitments are backed by the Brazilian environmental legislation, such as the National Plan for the Recovery of Native Vegetation (PLANAVEG; Brasil, 2017) and the Native Vegetation Protection Law (Law nº 12651; Brasil, 2012a). The latter requires land owners to protect native vegetation within rural properties and the compliance with this legislation would increase native vegetation cover in the Atlantic Forest from 28% to 35% (Rezende et al., 2018). Brazil is also committed to a number of national initiatives, such as Pacto Mata Atlântica (2009), which articulates stakeholders from different sectors to achieve the goal of restoring 15 million hectares of forests by 2050.

Recently, the city of São Paulo experienced a serious water crisis, which brought out the urgency to take action on water security. Our results highlight the potential of reforestation of the Tietê basin to improve water availability for the MRSP. Although large-scale reforestation in urban areas is not feasible, government measures include the creation of linear parks and increasing riparian forest cover for the Alto Tietê sub-basin as part of a mitigation strategy (Nobre et al., 2010). In addition to green areas expansion, these measures contribute to soil permeability improvement, increasing water retention capacity during flood periods, reducing floods and protecting channelized watercourses (Nobre et al., 2010). In Cantareira State Park, where crucial river springs for water supply emerge, deforestation has been reduced to zero and reforestation has begun to take place (SOSMA/INPE, 2018).

Reforestation of the Tietê river basin, however, will not suffice to restore or improve all hydrological parameters included in this study. We project, for instance, that soil

erosion will increase in the future, even if an intangibly high proportion of the basin is reforested. In this case, sustainable agricultural practices are needed to offset the tendency towards high siltation rates in the region. One interesting management strategy is to adopt "straw mulching" in croplands. This farming technique improves water use efficiency and is, therefore, recommended as a sustainable agricultural practice (Yan et al., 2017), and is encouraged by the Federal Government through benefits and credits to farmers (Brasil, 2012b).

Brazil's numerous reforestation commitments and initiatives are gradually improving the total forest cover area in the Brazilian Atlantic Forest. Deforestation in the biome, including São Paulo state, is close to zero, and the total forest cover is slowly increasing due to natural recovery and reforestation initiatives (e.g. Rezende et al., 2015; Silva et al., 2016). The most recent estimate reveals that the current vegetation cover equals 32 million hectares of native vegetation (or 28% of the original area, as mentioned above), rescuing the biome from the stigma of a "hotspot" and leading to a so-called status of a "hopespot" (Rezende et al. 2018). Similarly, Payment for Ecosystem Services (PES) are economic incentive programs that are also promoting forest cover regeneration; *Produtor de Água* and *Conservador das Águas* are two of the most well-established PES programs in Brazil (Ruggiero et al., 2019). Restoring forests in the Tietê basin have the potential to not only improve water safety *per se*, but also the provision of many other ecosystem services, whether directly linked to water — such as food security, human health and sanitation — or not linked to water — such as biodiversity, climate (from micro to global scales), air quality, and cultural services (MEA, 2005).

4. Conclusions

Our results corroborate the general trend of water quality improvement with increased forest cover (or reduced agricultural cover) driven by reduced agricultural and livestock inputs. We also found an improvement in water quantity with increased forest cover, but only in the southern portions of the basin. The negative effects of climate change were projected mainly in urban areas, which are not eligible for reforestation and, therefore, do not benefit from its buffering effect. We hope this study stimulates Brazilian decision makers to adopt reforestation of the Tietê water basin as a key water management strategy for the region, in order to improve water availability, security and well-being of millions of people.

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Appendix - Pairwise statistical tests (level of significance = 0.05) between each scenario and the baseline for water quality (a) and quantity (b) parameters by 2070 in Tietê basin, São Paulo, Brazil.

	Water Quality (a)			**Water Quantity (b)**		
	Pollution Footprint	**Sewage Footprint**	**Soil Erosion**	**Water Balance**	**Water Stress**	**Runoff**
Kruskal Wallis Test	H = 2106.1 df = 10 p-value $<2.2e^{-16}$	H = 318.85 df = 10 p-value $<2.2e^{-16}$	H = 21.069 df = 10 p-value = 0.02062	H = 2106.7 df = 10 p-value $<2.2e^{-16}$	H = 1000.7 df = 10 p-value $<2.2e^{-16}$	H = 92.134 df = 10 p-value = $2.019e^{-15}$
Post-Hoc Dunn Test						
Deforestation w/o CC	$3.02e^{-53}$ **	$9.14e^{-11}$ **	1	$5.6e^{-04}$ **	0.0381 *	1
Deforestation with CC	$8.92e^{-48}$ **	$3.35e^{-14}$ **	1	1	0.893	1
50% Reforestation w/o CC	1	$6.69e^{-29}$ **	1	$4.44e^{-38}$ **	$3.95e^{-05}$ **	0.361
50% Reforestation with CC	1	$6.04e^{-26}$ **	1	$8.3e^{-66}$ **	$1.14e^{-35}$ **	0.386
100% Reforestation w/o CC	$5.15e^{-27}$ **	$2.81e^{-40}$ **	0.41	$2.73e^{-97}$ **	$1.5e^{-49}$ **	$1.44e^{-04}$ **
100% Reforestation with CC	$2.49e^{-28}$ **	$4.27e^{-44}$ **	0.4	$3.01e^{-138}$ **	$8.37e^{-66}$ **	$7.29e^{-04}$ **

Legend: climate change scenarios: “with CC” – with climate change, “w/o CC” – without climate change; H – Kruskal Wallis test results; df – degrees of freedom; p-values: * – p<0.05, ** – p<0.001; the numbers shown in the cells for “Post-Hoc Dunn Test” are the p-values.

Table 1 - Hydrological parameters analyzed in scenarios of land conversion and climate change in Tietê basin, São Paulo.

Parameter	Definition	Unit
Quantity		
Water Balance[1,2,3]	Annual total water balance is the incoming rainfall and fog minus outgoing actual evapotranspiration[*,3] (from vegetation, soil and free water surfaces) - i.e. the water available as a resource at the land surface	mm/yr
Water Stress[4]	Mean annual water stress is the ratio of water use (demand) to availability (supply), where supply as the simulated water balance (i.e. after evaporative water use) per person and demand given as population multiplied by a user-defined per capita domestic and industrial demand	% of demand unavailable or contaminated
Runoff[2]	Total annual runoff is water balance cumulated downstream – i.e. a measure of surface water streamflow	Km^3
Quality		
Pollution Footprint[4,5]	The Human Footprint on Water Quality (HFWQ) is the percent of runoff at any point that fell as rainfall on potentially contaminating land uses upstream. It is calculated as cumulated downstream runoff from polluting (e.g. agriculture) and non-polluting (e.g. natural land) land uses, with the polluted runoff then expressed as the proportion of total runoff	% contamination
Sewage Footprint[6]	The Human Footprint on Water Quality (diarrheal disease; HFWQ[DD]) is calculated in a similar manner	% contamination

	as HFWQ but the source areas include only land uses with vectors of diarrheal disease by potential sources (i.e. with human and livestock headcount data), ignoring other potential polluting land uses used in HFWQ	
Soil Erosion[2]	Annual total net soil erosion is the gross soil erosion by wash minus deposition	mm/yr

Legend: * – actual evapotranspiration: total annual actual evapotranspiration as determined by available energy and vegetation cover and properties. References: [1] – Mulligan et al. (2011), [2] – Mulligan (2013), [3] – Mulligan (2019), [4] – van Soesbergen & Mulligan (2014), [5] – Mulligan (2009), [6] – Herrera et al. (2017).

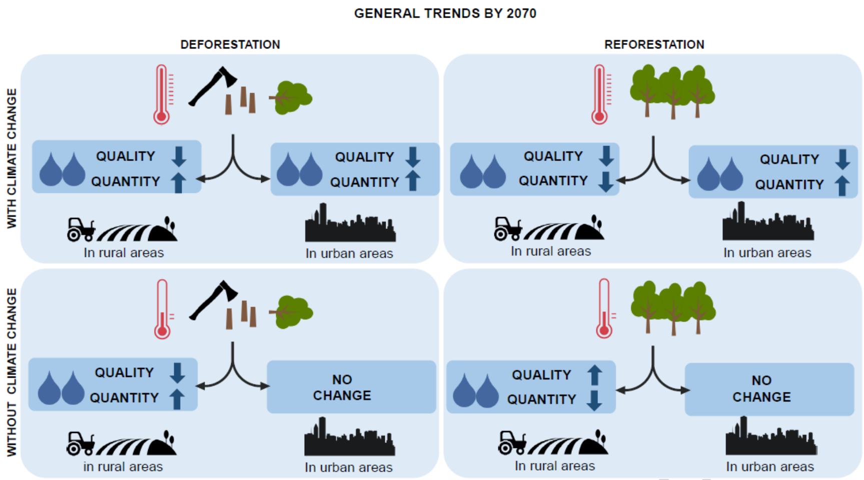
Table 2 - Summary statistics of the absolute values of water quality parameters by 2070 in Tietê basin under different forest cover and climate change scenarios. Values in cells: mean (standard deviation; minimum value–maximum value).

Scenario	Pollution Footprint (%)	Sewage Footprint (%)	Soil Erosion* (mm/yr)
Baseline	1.58 (3.24; 0.00–34.52)	3.3 (3.72; 0.00–34.84)	0.45 (9.8; -0.04–219.1)
Deforestation w/o CC	1.61 (3.78; 0.00–35.72)	6.16 (4.10; 0.00–36.55)	0.457 (9.99; -0.04–223.34)
Deforestation with CC	1.49 (3.68; 0.00–34.14)	6.01 (4.05; 0.00–35.05)	0.47 (10.29; 0.04–230.14)
50% Reforestation w/o CC	0.85 (2.91; 0.00–31.67)	3.17 (3.58; 0.00–33.21)	0.44 (9.53; -0.04–213.01)
50% Reforestation with CC	0.9 (2.97; 0.00–32.3)	3.19 (3.6; 0.00–33.26)	0.45 (9.86; 0.04–220.53)
100% Reforestation w/o CC	0.65 (2.12; 0.00–26.85)	1.32 (3.35; 0.00–29.76)	-3.015e-05 (0.0007; -1.5e-02–2.34e-04)
100% Reforestation with CC	0.6 (2.16; 0.00–28.82)	1.28 (3.36; 0.00–30.31)	-3.07e-05 (0.0006; -1.53e-02–2.46e-04)

Legend: (*) Soil erosion – gross soil erosion minus deposition (negative values mean deposition is higher than erosion).

Table 3 - Summary statistics of the absolute values of water quantity parameters by 2070 in Tietê basin under different forest cover and climate change scenarios. Values in cells: mean (standard deviation; minimum value–maximum value).

Scenario	Water Balance (mm/yr)	Water Stress (%)	Runoff (Km^3)
Baseline	502.4 (134.67; 102.6–1327.3)	32.53 (11.08; 0.00–39.58)	54.42 (0.41; 0.04-4277)
Deforestation w/o CC	528.1 (138.01; 102.6–1351.9	31.94 (10.98; 0.00–37.5)	55.19 (0.41; 0.04-4340)
Deforestation with CC	502.8 (152.56; 86.0–1363.1)	32.66 (11.18; 0.00–37.5)	55.8 (0.42; 0.04-4393)
50% Reforestation w/o CC	401.5 (136.42; 102.6–1271.4)	33.47 (11.18; 0.00–41.67)	52.48 (0.39; 0.04-4121)
50% Reforestation with CC	359.6 (153.04; 86.0–1275.7)	34.81 (11.71; 0.00–45.83)	53 (0.39; 0.04-4170)
100% Reforestation w/o CC	310.68 (144.8; 88.59–1226.28)	35.7 (12.03; 0.00–45.83)	51.02 (0.38; 0.04-4012)
100% Reforestation with CC	261.36 (164.48; 69.05–1227.46)	36.84 (12.54; 0.00–45.83)	51.77 (0.39; 0.04-4082)



Graphical abstract

Highlights

- The role of forests to mitigate impacts on water was assessed in Brazil
- Scenario-modelling regarding biosphere, hydrosphere and anthroposphere was used
- Climate changes' impacts were more pronounced in urban areas
- The increase in water availability is the greatest benefit of reforestation
- Sustainable agricultural practices are needed complement water management